

Tree Damage in Mechanized Uneven-aged Selection Cuttings

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Abstract

The amount of selection cuttings in uneven-aged forest stands is supposed to increase in Finland with the new Forest Act. In uneven-aged management, it is estimated that the cutting could be repeated every 15–20 years with the removal of around 100 m³/ha, depending on the site type and stand growth. This interval and volume highly depend on survival of lower canopy trees in cuttings. The number of these trees (2.5–15 m in height) is typically limited. Felling larger trees from above means a high damage risk for smaller trees and also restricts the harvesting outside the heavy frost period due to top damage risk. Damage to trees taller than 2.5 meters was studied in three selection cutting stands. Mechanized harvesting (harvester – forwarder) was carried out in late winter with no frost, which is the optimal time for selection cuttings. On the average 21.5% of the remaining trees were damaged. The percentage of damage to smaller (2.5–10 m) trees was highest, 28.4%. Stem damage and breakage were the most common types of injury. A logistic mixed model was used to model the probability of tree injury (uninjured/injured). Distance from the nearest removed tree, harvested basal area within 25 m of the tree and diameter of the tree were the explanatory variables taken into the model. The model discrimination ability by the ROC curve was 72.2%. With a classification cutpoint of 0.5 for the model fitted injury probabilities, the rate of correct classification was 79.1%. There is a need to develop optimal working practices for mechanized selection cuttings. Information on the stand structure, practical operator tutoring and knowledge of the goals of the forest owner are needed for successful harvesting implementation.

Keywords: uneven-aged forest management, selection cutting, mechanized harvesting, tree damage, spatial analysis.

1. Introduction

Current forest management in Finland is based on even-aged management. The use of alternative forest management methods including selection cuttings has been marginal concentrating to urban forests, landscape protection areas, valuable habitats, riparian and other buffer zones (e.g. Hyvän metsänhoidon suositukset 2006). The amount of selection cuttings in uneven-aged forests has been only some thousands of hectares per year (Selvitysraportti metsälain 6 §: n 2003). The structure of private forest ownership has changed and today 36% of forest owners live outside the municipality, where their forest property is located (Hänninen and Karppinen 2010). Many forest owners are not highly dependent of forest income anymore and emphasize multiple values in management deci-

sions. Even more than a half of the forest owners are satisfied with the current forest management practices, one of six forest owners feels unsatisfied especially with clear cuttings, lack of management alternatives, soil preparation and damage caused by heavy machinery. The attitude towards uneven-aged forest management is positive. Near half of forest owners see a potential for uneven-aged management, and 27% of forest owners are ready to try it at least in a part of their forest property (Kumela and Hänninen 2011).

Since 2010 there has been a renewal process of the Finnish Forest Act. The new Forest Act (<http://www.finlex.fi/fi/laki/smur/1996/19961093>) was set in the beginning of 2014, leaving more freedom and choices in forest management. The demand for alternative forest management is likely to increase, and forest own-

ers as well as professionals need more information on effects and implementation of alternative management practices. Compared to even-aged management, our knowledge on alternative methods is vague. This lack of knowledge covers stand development and production, economy, ecology as well as harvesting.

Kuuluvainen et al. (2012) present a thorough review of even-aged and uneven-aged forest management in Boreal Fennoscandia. They conclude that, although the number of relevant studies has increased in recent years, the ecological and economic performance of alternative management methods still remains insufficiently examined. The uneven-aged forest management consists of a range of methods, in which the forest cover is only partially removed. In this definition of uneven-aged management, the tree age distribution does not necessarily conform to the reverse J-shaped form and an uneven-aged forest can also consist of spatially segregated groups of tree age classes created by the group selection method. This broader group of uneven-aged management is also referred to as continuous cover forestry (Pommering and Murphy 2004).

Pukkala et al. (2010) optimized the structure and management of uneven-aged stands in Finland. The post thinning diameter distribution of stands was optimized with 20-year cutting cycle when aiming at maximum economic profitability. Spruce stand optimizations were done for fertile and medium sites. The optimal post-thinning distributions had a truncated reverse J shape. The harvesting removal on fertile site was 145 m³/ha and 95 m³/ha on medium site. Optimization of economic result meant removing all log-sized trees at 20-year intervals. Increasing discounting rate and decreasing site productivity improved the relative performance of uneven-aged management compared with even-aged management.

Near 100% of harvesting carried out by the forest industry in Finland is done with the mechanized cut-to-length method. In selection cuttings, harvesting carried out by the forest owner would be a proper alternative, making also the cuttings with small removals possible. However, the ability of forest owners living in towns to carry out cuttings themselves is limited. If selection cuttings are carried out on a larger scale, mechanized cutting is the main alternative. The efficient use of machinery needs sufficient removals, at least 70–100 m³/ha. In selection cuttings, the removal mainly consists of larger trees. Felling and processing of these trees means a high risk of damage to smaller trees and saplings.

In uneven-aged stands, future development, as well as harvesting conditions, depend on the structure

of the stand, harvesting intensity, forest regeneration, but also on the amount of damage in harvesting. In Finland, Norway spruce (*Picea abies* (L.) Karst) stands have the highest potential for uneven-aged management on a commercial scale (Valkonen and Maquire 2005, Lähde et al. 2002), but they also have high risk of pathogen infections following harvesting damage (Hakkila and Laiho 1967, Isomäki and Kallio 1974). There is also a high risk of *Heterobasidion* root rot in all tree size classes in uneven-aged stands (Piri and Valkonen 2013). Knowledge on harvesting damage in selection cutting in Scandinavia is limited, and it has mainly focused on small saplings. Granhus and Fjeld (2001) found that the injury probability of saplings depends both on stand and operational characteristics, the most important factor being the interaction between these two variables. Sapling height and spatial distribution of saplings relative to the strip roads and larger trees of the residual stand represented stand characteristics, whereas operational characteristics were described by the operational method and harvesting intensity.

Surakka et al. (2011) studied injuries on 0.5–2.5 m saplings. Depending on the stand, the percentage of injured saplings varied between 17.6–61.0%. The distance of the sapling to the nearest strip road, sapling height, harvested basal area within a distance of 25 m from the sapling and sapling distance to the nearest remaining tree explained the probability of injury. Saplings near the strip road and taller saplings were more prone to damage than saplings located further away from the strip road and small saplings.

Earlier Fjeld and Granhus (1998) compared the effect of two operating systems (motor-manual cutting followed by cable skidding and one-grip harvester followed by forwarding) and three harvest intensities on the injury rate in multi-storied Norway spruce stands. The average injury rate was higher in mechanized than in motor-manual harvesting. The largest differences were at high harvest intensities in densely stocked stands. The average injury rate was 13% for small trees (diameter under 10 cm) and 7.5% for larger trees.

The long term future of an uneven-aged stand depends on ingrowth, survival and height growth of small trees. The growth of small trees is very low, and with average growth rates, it takes about 60 years for a spruce germinant to achieve 1.3 m in height (Eerikäinen et al. 2014). Thus shorter term harvesting possibilities are highly based on survival of smaller and medium-sized trees in cuttings. If a significant percentage of these trees is damaged in harvesting, repeated cuttings every 15–20 years are not possible.

2. Aim of the study

The aim of this study was to evaluate the amount, type and quality of damage to trees taller than 2.5 m in mechanized selection cutting (cut-to-length method, harvester – forwarder) of uneven-aged Norway spruce stands and to construct a model for the description of damage.

3. Materials and methods

3.1 Study stands and measurements

The harvesting experiments were carried out in three Norway spruce dominated stands located in Sounenjoki, Northern Savonia region. The sites represented the submesic *Myrtillus* type and the mesic *Oxalis – Myrtillus* in terms of Cajander (1909). The stands (A, B and C, 1.08, 0.85 and 0.42 hectares, respectively) were earlier harvested motor-manually in 1987. After that, the stands A and B were harvested again in 1999, A mechanically with a one-grip harvester and B motor-manually. All these harvesting operations aimed to an uneven-aged structure. The whole strip road network was already in place after these previous entries, with a few additions. The average distance between strip roads was 25, 27 and 23 m in stands A, B and C, respectively.

Before harvesting, trees of commercially valuable tree species (i.e. Norway spruce, Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth), downy birch (*B. pubescens* Ehrh) and aspen (*Populus tremula* L.) with a height of > 2.5 m were mapped (x and y coordinates) and measured for diameter at breast height (d). Tree heights were measured from a sample of 75–125 trees per stand. The sample trees were used to estimate the tree heights for the rest of the trees and the stem volumes for all the trees. The tree heights were estimated with the models by Näslund (1937), and the stem volumes with the models by Laasasenaho (1982) and Kärki et al. (1999).

Trees to be felled were selected in three phases (Surakka et al. 2011): 1. trees located on the strip roads, 2. trees of weak health or poor technical quality, 3. Single tree selection from the remaining stand using a computerized tree selection procedure, with a classical negative exponential distribution (de Liocourt 1898) as the structural framework.

The target basal area after harvesting was set at 20 m²/ha, and the trees to be removed were marked before cutting. Stand parameters before and after harvesting are summarized in Table 1 and diameter distributions are presented in Fig.1.

Table 1 Stand characteristics before and after cutting

	Stand	A	B	C
Before cutting	Volume, m ³ /ha	289	296	295
	Basal area, m ² /ha	27.9	29.2	31.1
	Stems/ha, $h > 2.5$ m	766	1021	1262
Remaining stand	Volume, m ³ /ha	185	200	173
	Basal area, m ² /ha	18.3	20.3	18.7
	Stems/ha, $h > 2.5$ m	625	891	947
Removal	Volume, m ³ /ha	104	96	122
	Basal area, m ² /ha	9.6	8.9	12.4
	Stems/ha, $h > 2.5$ m	141	130	315

Cutting was carried out with a one-grip harvester Ponsse Ergo HS16 in late March and forwarding in early April 2007 with a Ponsse Buffalo forwarder. The temperature varied from –1 to +13 °C, snow depth from 0 to 20 cm, and visibility was good during the cutting. Two skilled harvester operators carried out the cuttings. The harvester and forwarder drivers were instructed to prevent damage to both trees and saplings. The harvester operators were instructed to fell the marked trees away from the strip roads. After cutting, the damage caused by the harvester was marked and inventoried to keep it separate from the damage caused by forwarding.

After harvesting, the total number of remaining trees higher than 2.5 m was 1808. Injuries were assessed for each remaining tree. Trees were classified into a) uninjured, b) injured, will survive or c) fatally injured. Fatally injured consists of perished small trees, felled trees and trees broken near the ground. The damage type of a tree could be one of the following (for injury b) types 1–6 and for injury c) types 2 or 7 were possible): 1) stem damage including root collar damage, 2) stem breakage, 3) root damage, 4) crown damage, 5) tilt, 6) several types of damage or 7) disappeared. A stem or root damage was recorded, if the damage area was at least 1 cm². Damage size was measured at two dimensions, lengthwise and crosswise. Distance from root collar to the beginning of the damage was measured for stem and root damage. Stem and root damages were further divided into bark damage (bark removed) and wood damage (wood smashed), depending on how deep the damage was. For stem breakage, the height of the breaking point was measured. Crown damage was recorded if the green crown loss was noticeable (more than 10% of

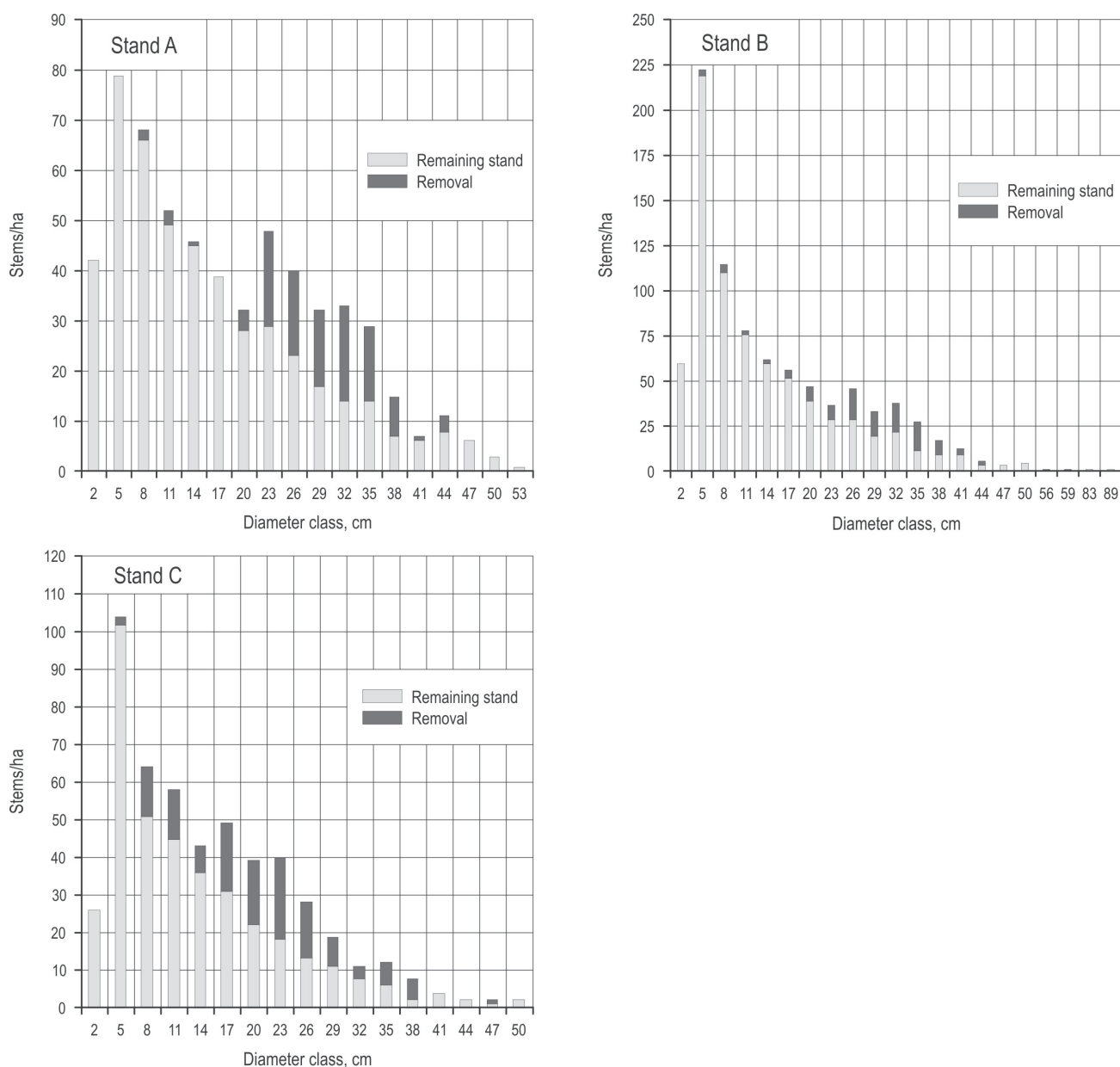


Fig. 1 Diameter distributions of study stands

green crown volume). A tilt was recorded if a tree tilted at least 10 degrees from its original (vertical) position. Trees that were not found after harvesting were entered as »disappeared«. Usually they were smaller trees often under piles of slash or logs. For the modeling purposes, we simplified the injury classification into two groups: uninjured and injured.

3.2 Modelling

Variables affecting the probability of a tree being injured y_{ij} (a tree j sampled from a stand i) were explored using a logistic mixed model:

$y_{ij} = 1$, if a tree was injured (living or dead),
probability = p_{ij}

$y_{ij} = 0$, if a tree was uninjured, probability = $1 - p_{ij}$

$y_{ij} \sim \text{Binomial}(1,)$

$$\ln \left(\frac{p_{ij}}{1 - p_{ij}} \right) = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2ij} + \beta_3 (X_{1i} \times X_{2ij}) + \dots + u_i \quad (1)$$

where p_{ij} is the modelled injury probability, \ln is the natural logarithm function, $\beta_0, \beta_1, \beta_2, \dots$ are fixed effects parameters to be estimated, X_{1i}, X_{2ij}, \dots are stand-specific (i) or tree-specific (ij) explanatory variables (con-

Table 2 Statistics of tested possible explanatory variables for the injury model

Variable	<i>n</i>	Minimum	Median	Mean	Maximum
Tree species	1808	0.00	1.00	0.82	1.00
Diameter	1808	1.00	10.80	14.28	90.00
Height	1808	2.54	11.60	12.73	35.50
Basal	1808	0.00	6.21	6.08	12.73
Stems	1808	0.00	96.77	105.78	325.95
Distance	1808	0.10	4.14	6.05	33.96
Distance_2	1808	0.65	5.93	7.51	34.95

Tree species – tree species group (1 = coniferous tree, 0 = broadleaved tree)

Diameter – diameter of tree at breast height, cm

Height – height of tree, m

Basal – harvested basal area at distance of 25 m from the tree, m²/ha

Stems – harvested number of trees at distance of 25 m from the tree, stems/ha

Distance – distance of tree to the nearest removed tree, m

Distance_2 – distance of tree to the centre of the nearest strip road, m

tinuous or dummy), »×« denotes an interaction effect, and u_i is a random stand effect, $u_i \sim \text{Normal}(0, \sigma_u^2)$.

Adding the stand as a random, categorical variable to the model takes into account the possible correlation of the tree observations within the stands. In this data, all the explanatory variables were tree-specific and continuous except the categorical variable tree species group (coniferous or broadleaved). To observe better the effect of spatial variation on a tree injury, several tree-specific explanatory variables were performed (Table 2) from the mapped tree data to describe the remaining stand around the tree. Various transformations of the continuous explanatory variables or interactions of the explanatory variables were also checked in candidate models.

The model fit was assessed by the discrimination and the correct classification of the data, using the fixed part of the model to predict injury probability p_{ij} . From the model (1) we get:

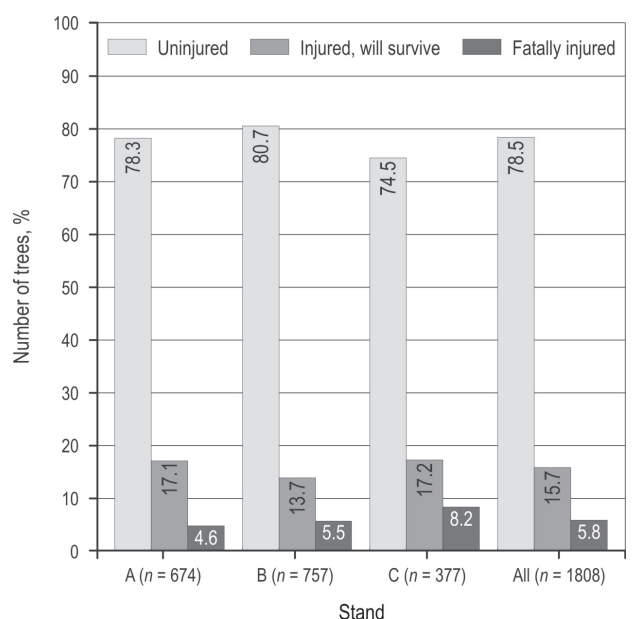
$$p_{ij} = \frac{\exp(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2ij} + \beta_3 (X_{1i} \times X_{2ij}) + \dots)}{1 + \exp(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2ij} + \beta_3 (X_{1i} \times X_{2ij}) + \dots)} \quad (2)$$

where \exp is the exponential function.

The area under the ROC curve is a measure of the discrimination ability of a statistical model for a binary response variable: it is the probability (or the percentage) that, for a randomly selected pair of an injured and uninjured tree, the model p_{ij} is greater for the injured one. The probability 0.5 was used as a cut-point value for the model classification of an observed tree: if the model $p_{ij} \geq 0.5$, the tree was classified

injured (value 1 is closer), otherwise uninjured (value 0 is closer). The cutpoint 0.5 does not usually give the best correct classification result, but it tries to be an objective cutpoint. After the model classification the rate of correct classification could be counted by cross-tabulating observed and predicted tree injuries.

The analyses were carried out by the SAS statistical software, version 9.3. (SAS Institute Inc. 2014). The GLIMMIX procedure was used for the model estimation, the LOGISTIC procedure for the ROC curve calculation and the FREQ procedure for the cross-tabulation.

**Fig. 2** Percentages of uninjured and injured trees by stands

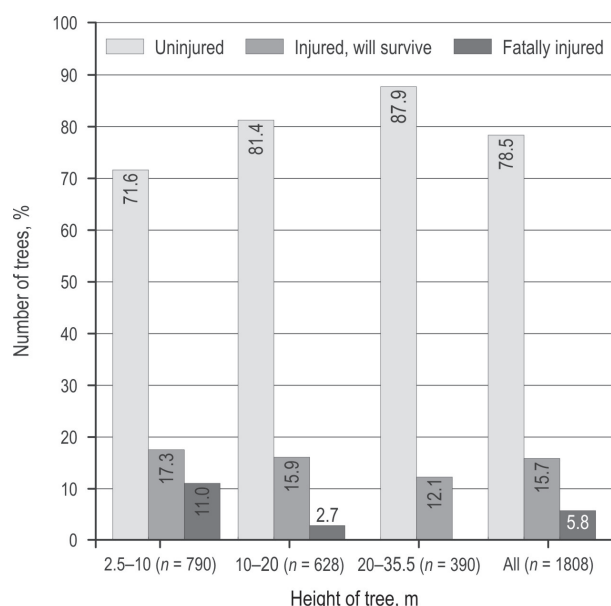


Fig. 3 Percentages of uninjured and injured trees by height classes

4. Results

4.1 Amount, type and severity of injury

Fig. 2 presents the percentage of trees of the stands A–C divided into three classes: uninjured, injured, will survive fatally injured. The percentages of trees in different height classes are shown in Fig. 3, and percentages of different damage types in Fig. 4.

Stem damage and stem breakage were the most common damage types, together affecting near 70% of the damaged trees. Stem breakage or disappearing occurred mostly for lower canopy trees, and these trees formed the injury class »fatally injured«. The percentage of root damage was under 10% for all damaged trees, but nearly 50% for damaged trees taller than 20 m. Near 15% of the damaged trees had several types of

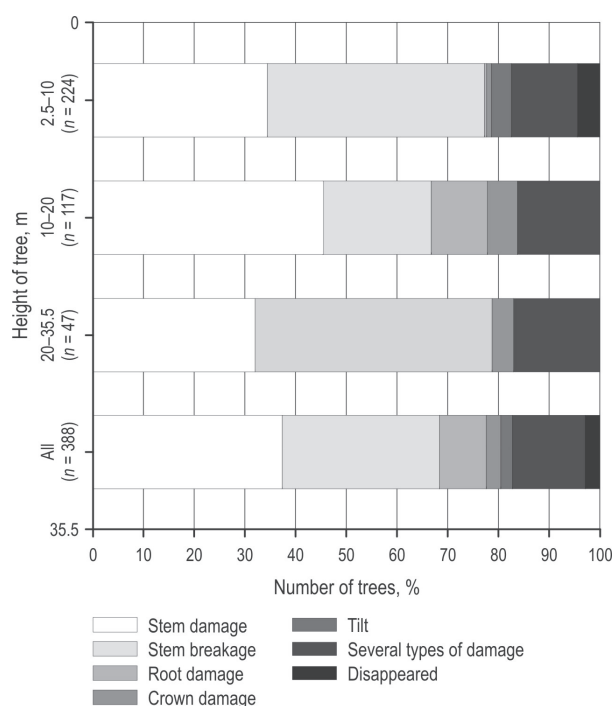


Fig. 4 Percentages of injured trees in damage types by height classes

damage. Most damage, 88.4% of all damage, was caused in cutting. Forwarding caused 11.6% of damage, and near all root damage was caused in forwarding. The distribution percentiles of size distributions and locations of stem and root collar damage are presented in Table 3 and distribution percentiles of stem breakage heights in Table 4.

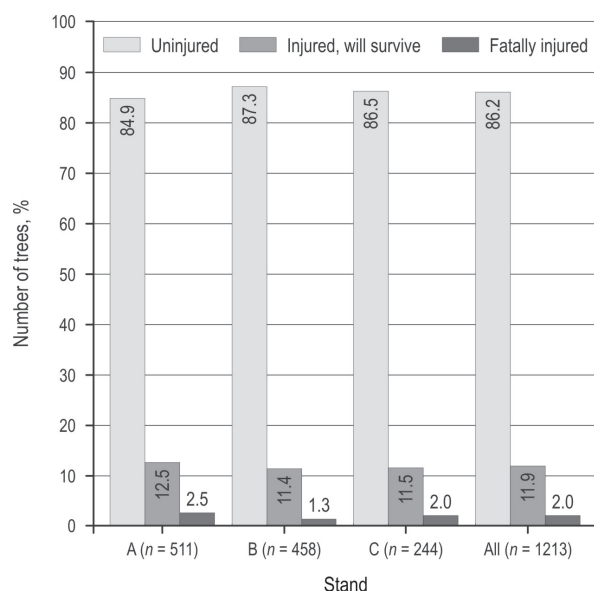
The amount of damage was also calculated according to the classification system of the Forest Act, where only trees with $d_{1.3} \geq 7$ cm are included and for superficial stem damage the minimum wound size is 12 cm² under $d_{1.3}$ or 30 cm² in the whole tree (Fig. 5).

Table 3 Distributions percentiles (minimum, lower quartile, median, upper quartile and maximum) of stem damage area (cm²) and the distance to lowest damage point from root collar (dm, in parenthesis) by damage type and height of tree (m)

Damage type	Height of tree, m	<i>n</i>	Minimum	Lower quartile	Median	Upper quartile	Maximum
Bark	2.5–10	84	1 (0)	8 (2)	15 (5)	45 (8)	380 (35)
	10–20	62	2 (0)	8 (5)	20 (10)	48 (18)	1600 (78)
	20–35.5	19	5 (0)	21 (4)	100 (9)	600 (27)	4200 (70)
Wood	2.5–10	22	15 (0)	36 (2)	120 (5)	210 (7)	300 (33)
	10–20	10	6 (0)	60 (2)	155 (5)	320 (16)	560 (42)
	20–35.5	3	20 (1)	20 (1)	75 (16)	400 (70)	400 (70)

Table 4 Distribution percentiles (minimum, lower quartile, median, upper quartile and maximum) of stem breakage height from root collar (dm) by height of tree (m)

Height of tree, m	<i>n</i>	Minimum	Lower quartile	Median	Upper quartile	Maximum
2.5–10	100	0	0	0	20	95
10–20	30	0	4	53	90	200
20–35.5	1	200	200	200	200	200

**Fig. 5** Percentages of uninjured and injured trees by stands with injury classification according to the Forest Act

4.2 Model for spatial variations in the probability of injury

In the modelling, there were 1420 uninjured and 388 injured trees. The following model was used to explain the injury probability of the tree (3):

$$\ln\left(\frac{p_{ij}}{1-p_{ij}}\right) = -0.685 - 0.195 \times \text{DISTANCE} - 0.040 \times \text{DIAMETER} + 0.117 \times \text{BASAL} \quad (3)$$

Where:

DISTANCE – distance of tree to the nearest removed tree, m

DIAMETER – diameter of tree at breast height, cm

BASAL – harvested basal area at distance of 25 m from the tree, m²/ha

All the explanatory variables were clearly significant in the model: $p < 0.0001$ (F -test with 1 and 1802

degrees of freedom). The area under the ROC curve for the model was 0.722 (72.2%), which is considered acceptable discrimination ability by Hosmer and Lemeshow (2000). With a classification cutpoint of 0.5 for the model fitted injury probabilities p_{ij} using the formula (2), the rate of correct classification was 79.1% (uninjured 99.2%, injured 5.4%).

The influence of the explanatory variables to the injury probability of a tree in the model is presented in Fig. 6.

5. Discussion

The study material used in this study was collected in 2007 and was earlier used in modelling damage to 0.5–2.5 m saplings (Surakka et al. 2011). Almost the entire strip road network of the study stands was established in earlier cuttings, and thus there was very little removal from strip roads. Trees to be removed were marked before cutting, which is not typical in practical harvesting operation, and the harvester operators were instructed to fell the marked trees away from the strip roads. As the felled trees were mainly large, the possibility to lift them under felling to the direction of the strip roads would have been limited.

However, utilizing the strip road openings in felling could have decreased the amount of damage to some extent. Miettinen (2005) simulated the effect of harvester working technique on damage risk for saplings in selection cutting on three permanent study plots (Eerikäinen et al. 2007), where the locations of larger trees and saplings had been mapped. A working method where all trees were felled into the stand away from the strip roads was compared with a method where trees nearer than five meters from the strip road were directed towards the strip road, also lifting them on the strip road when possible. When felling trees into the stand without utilization of the strip roads, 45% of saplings were exposed to damage. When strip roads were used, the percentage of damaged saplings was somewhat lower, at 38%.

After harvesting, injuries were assessed for each remaining tree. This kind of total inventory, where all remaining trees on the area of 2.35 hectares were as-

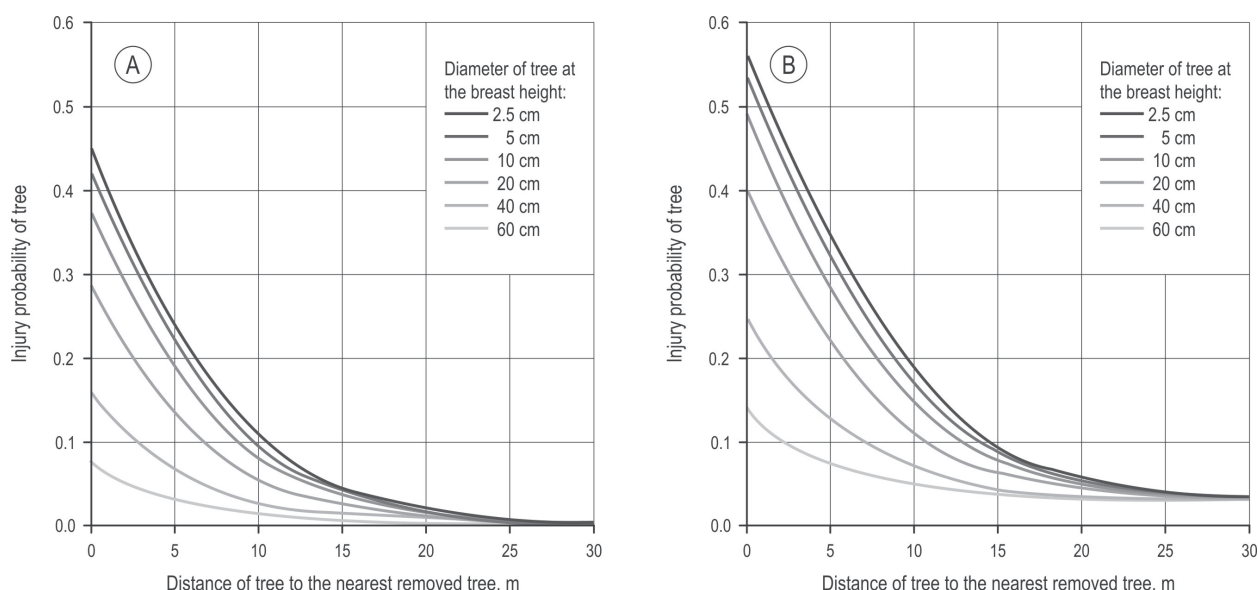


Fig. 6 Influence of harvested basal area at distance of 25 m from the tree ($A = 5$ and $B = 10 \text{ m}^2/\text{ha}$), diameter of tree at breast height (cm) and distance of tree to the nearest removed tree (m) on injury probability of tree

essed, is a laborious operation. However, when areas with suitable uneven-aged structure for the study were hard to find, total measurement of quite limited areas allowed collecting a proper material for modelling. Typically the damage inventories are made on sample plots. When quality of harvesting is followed by Finnish Forest Centre, circular sample plots of 100 m^2 are used. When studying harvesting quality and tree damage in even-aged stands, Sirén (1998) used 240 m^2 rectangular sample plots divided into eight 30 m^2 measuring zones. In the study of selection cutting damage by Fjeld and Granhus (1998), the post-harvest inventory was based on 4 m wide and 24 m long rectangular sample plots stretching from strip road centre to strip road centre. Trees were classified into uninjured, injured, will survive and fatally injured. For small lower canopy trees the damage was often fatal, and the class fatally injured consists of small trees with severe damage. In most damage inventory methods (Eriksson 1981, Björheden and Fröding 1986, Sirén 1998), tree damage is monitored only for trees with commercial value.

In this study, 78.5% of the trees had no damage, while 15.7 trees were damaged but will survive and 5.8% were fatally damaged. Near 90% of the damage was caused by the cutting operation. The trees with very severe damage were mainly 2.5–10 m tall lower canopy trees, which had stem breakage or had disappeared. In the study of Fjeld and Granhus (1998), the percentage of damaged trees was 8.7–13.7%. In their study the injury rate increased with harvesting intensity, and was higher in mechanized than in motor-manual cutting. The injury rates were highest near strip roads, where the injury rates with both methods exceeded 20%.

The probability of damage was explained by distance to the nearest removed tree, harvested basal area within 25 m from the tree and diameter of tree. The distance to the nearest removed tree best predicted the damage probability. The lower canopy trees have higher injury probability than larger trees. These explaining variables are logical. With increasing amount of work per area unit, the risk for damage increases. When larger trees are felled and processed, smaller nearby trees are at high risk for damage. The model for injury probability was able to correctly classify 79.1% of the trees as injured or not injured. In the model for sapling damage (Surakka et al. 2011), the rate of correct classification was 73.0%, and with model presented by Granhus and Fjeld (2001) 70.5%.

In Forestry recommendations (Äijälä et al. 2014), the amount of tree damage is one element of silvicultural harvesting quality. Finnish Forest Centre measures annually the quality of more than 200 thinning stands, and the percentage of damaged trees in 2013 was 3.6 (Korjuujälkitarkastukset 2013), which is quite typical in long run. If the percentage is over 15%, it exceeds the limit of the Forest Act. Although there is a large variation between stands, the limit of the Forest Act is seldom exceeded in even-aged stands.

In this study, the percentage of damaged trees after the classification of the Forest Act was 13.8%. As the amount of damage in good conditions carried out with skilled operators was near to exceed the limit, we can find that in selection cuttings it can be very difficult to reach low damage levels typical for even-aged stands. Also, new results (Hämäläinen 2014) on the amount of tree damage in uneven-aged stands show quite high

damage numbers and high damage risk especially in lower canopy trees.

High percentages of damaged trees with mechanized cut-to-length method have also been presented outside Scandinavia in even-aged stands. In Germany 12.6% of remaining trees were damaged (Sauter 1995). In North-America Bettinger and Kellogg (1993) reported very high damage numbers. In their study near 40% of remaining trees were damaged.

Košir (2008) modelled the amount of tree damage with motor-manual and cut-to-length methods in Slovenia. With motor-manual method, the share of injured trees in thinnings was 17–19% and with cut-to-length method 13–15%. During a 160-year rotation period 10 thinnings take place, and the total number of damaged trees continuously grows and reaches 90% at the end of rotation. The modelled percentage of damaged trees is very high, but a high share of damaged trees (64–70%) has also been recorded in old stands (Košir 1998).

There are many interesting study topics in selection cutting operations and working methods. As stand structures and goals of forest owners vary substantially, the harvester operator needs information on stand structure, slopes and soil bearing capacity. There are new interesting ways to utilize multi source information and operator tutoring in harvesting (Räsänen et al. 2014, Väättäinen et al. 2013). Selection cuttings are a challenging but interesting scene to test these tools.

6. References

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